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NAVIGATION AUTOMATION FOR THE *SOIL MOISTURE ACTIVE PASSIVE* OBSERVATORY

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Soil Moisture Active Passive (SMAP) is a NASA Earth science mission designed to measure soil moisture content and freeze/thaw cycles over a three-year period. This paper presents a 2-year summary of navigation performance, shows navigation compliance (and non-compliance) with Science Orbit Requirements, and describes how automated processes appreciably reduced the size of the navigation team.

INTRODUCTION

SMAP launched from Vandenberg Air Force Base on January 31, 2015 aboard a Delta-II launch vehicle and ascended to a temporary parking orbit. After the observatory separated from the booster, four commissioning maneuvers within one month raised SMAP's perigee and placed the spacecraft into a near-circular, polar, Sun-synchronous, 685-km high, 98.5-minute orbit, with an 8-day, 117-orbit repeat ground track. The fourth maneuver targeted the reference trajectory, a theoretical path that the operational spacecraft attempts to fly close to while gathering data in the Science Phase. Reaching the reference trajectory on April 8, 2015 marked the beginning of Science Phase. See Table 1 for details of the four commissioning maneuvers and Table 2 for a description of the reference trajectory.

Table 1. Maneuver Performance, From Launch to Science Phase.

Name	Mission Day	Date, UTC	Reconstructed ΔV, ms^{-1}	Error, σ
CAL1	34	March 5, 2015 17:25:03	1.28	-0.52
INC1	40	March 11, 2015 17:56:28	0.21	1.53
INP1a	45	March 16, 2015 17:03:24	4.68	-0.82
INP1b	45	March 16, 2015 21:14:30	1.09	-0.56
		Total ΔV:	7.26	

Table 2. Science Phase Reference Trajectory, epoch: April 8, 2015 20:12:56 UTC.

	Mean Elements	Osculating Elements
Semi-major Axis, km	7057.5	7066.6
Eccentricity	0.0011880	0.0012842
Inclination, deg	98.126	98.122
Argument of Perigee, deg	89.996	69.816
Right Asc. Of Asc. Node, deg	107.27	107.27
True Anomaly, deg	-89.997	-69.816

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SMAP CONFIGURATION

The observatory carries two L-band instruments: a radiometer and a synthetic aperture radar (the latter instrument failed on July 7, 2015). Both instruments share a 6-meter diameter mesh antenna, which rotates above the spacecraft bus at 14.6 rpm. The spacecraft bus is 3-axis stabilized using reaction wheel assemblies; magnetic torque rods de-saturate momentum accumulation on the wheels. Electrical power is supplied by a body-fixed solar array. A hydrazine blow-down propulsion system with eight small thrusters is employed for maneuvering and orbit maintenance. Four of the eight thrusters control yaw. The remaining four provide axial thrust as well as roll and pitch control. The average specific impulse is 216 s[1].

S-band doppler tracking data (as well as X-band for science data) are returned via NASA's Near Earth Network (NEN). Ground stations are located at four sites: Fairbanks, Alaska; Wallops Island, Virginia; Svalbard Island, Norway; and Antarctica. The NEN advertises its two-way, range-rate tracking data noise is less than 10 cm/s (1.5 hz), 3σ[2]. To date, NEN tracking data delivered to SMAP has exhibited a mean RMS residual equal to 6.4 +/-2.5 mm/s (0.095 +/-0.037 hz), an order of magnitude lower (Figure 1).

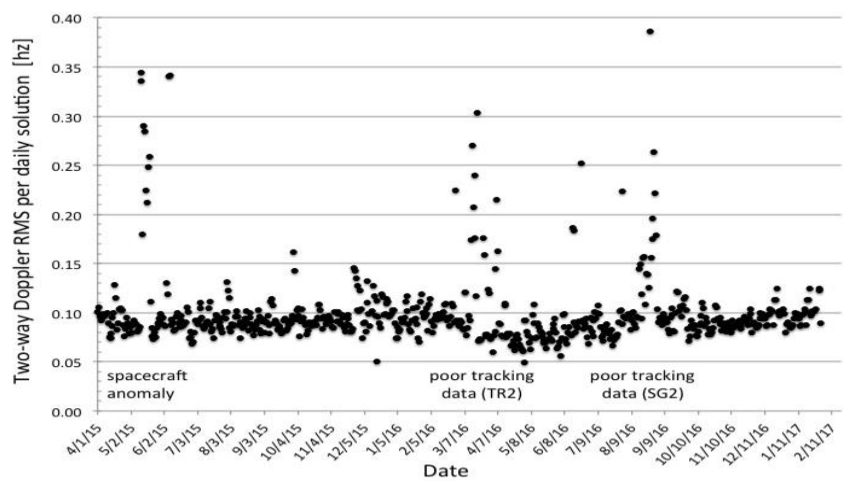

Figure 1. Tracking Data Noise, per day. Anomalies are noted.
TR2 is a TrollSat station in Antarctica; SG2 is a Svalbard station.

TARDIS

In the early stages of SMAP development, navigation analyses indicated that Science Requirements could be met only with *daily* deliveries of ephemerides to the scientists. Workforce considerations necessary to support this level of activity were anticipated to be considerable, thereby leading the Project to explore automation. The end result was the design and implementation of a sophisticated software package called TARDIS (Traceable Automation with Remote Display and Interruptible Scheduler)[3].

TARDIS is an agent (a shell) capable of scheduling and launching tasks. Tasks perform a job; the agent creates tasks when events occur. An event is user-defined and can be time-based (task starts at a specific time) or file-based (task starts upon appearance of a specified file). Tasks retire after accomplishing their job.

SMAP is the first JPL mission to certify and rely entirely on automation for end-to-end navigation operations and product deliveries. During Commissioning Phase (January 31 – April

8, 2015), Navigators performed orbit determination manually while TARDIS operated in shadow mode, allowing its performance to be assessed. After certification, TARDIS became prime for orbit determination (OD), maneuver reconstruction, and product deliveries. The routine nature of orbital operations has led to almost full reliance on TARDIS; the design of trim maneuvers remains the only function involving human input.

The Project's pre-launch requirement levied on TARDIS was a minimum success rate of 95% for all product deliveries. That is, assuming *daily* product deliveries, no more than 19 delivery failures per year when accounting for *all* sources of failure (since in round numbers 5% of 365.25 equals 19). As a corollary, when human backup is combined with TARDIS, the Project expected a delivery success rate greater than 97.5% (no more than 10 failures per year).

TARDIS became prime for operations on July 1, 2015 and continued the daily Commissioning Phase ephemeris delivery cadence (even though that demanding frequency is no longer strictly necessary – see the next section "Satisfying Science Requirements"). Its delivery success rate is 95% – equal to the levied requirement. See Table 3(A). Failures due to TARDIS-specific anomalies have occurred only 4 times – a success rate equal to 99.3%. See Table 3(B). The overall product delivery success rate (including human backup) is 99.5%.

TARDIS enabled team size consolidation – the human navigation team is 25% as large as it would have been without the automation. As a result, TARDIS will generate significant cost savings to the Project over the lifetime of the SMAP mission.

Table 3. TARDIS Operational Statistics, July 1, 2015 – February 1, 2017.

(A)

Automated Delivery	
Number Scheduled	582
Number Successful	553
Success Rate	95%

(B)

Failures (5%)	Instances
Procedural Error[1]	12
Bad Tracking Data[2]	6
External Reasons[3]	7
TARDIS[4]	4
Failures – all causes	29

1. Navigation implementation: algorithm shortcoming and/or incorrect calibration
2. Automation implementation: poor data is removed automatically, but the process is not 100% effective
3. Causes beyond user / Project control *e.g.* network failure
4. TARDIS algorithm deficiency

SATISFYING SCIENCE REQUIREMENTS

Table 4 shows the achieved science orbit. All orbit parameters are within specifications; however the orbit's projection onto the ground has not met requirements. This exception is discussed in more detail below.

Table 4. Achieved Science Orbit, epoch: February 1, 2017 00:00:00 UTC.

	Reference Orbit		Achieved Performance	
Orbit Parameter	Target Value	Margin 3σ	Largest Offset from Reference Orbit since April 8 2015	Error
Semi-major Axis, km	7057.5[1]	±8	0.231	0.09 σ
Eccentricity	1.188e-3[1]	±1e-3	-6.79e-5	0.2 σ
Inclination, deg	98.126[1]	±0.05	0.00366	0.2 σ
Arg of Perigee, deg	90.0[1]	±180	-3.50	0.06 σ
MLTAN[2], hh:mm:ss	18:01:30	±30 s	8 s	0.8 σ
Ground track at Ascending Node	Reference ground track	±20 km crosstrack	39 km	19 km beyond corridor
Altitude at equator	685 km[3]	±1 km radial	0.55 km	within corridor

1. Mean elements
2. Mean Local Time of Ascending Node
3. Osculating elements

Solar Flux

Solar flux and geomagnetic activity are parameters for modeling the dynamic atmosphere. Near-term flux predictions (up to 4-weeks) come from the Solar Weather Prediction Center[4]. SWPC predictions of less than 3-days are accurate; intermediate predictions between 3- and 27-days are less robust. *Long-term* flux predictions (beyond 27-days) come from Marshall Space Flight Center and are more speculative[5]. Nevertheless long-term predictions get applied during orbit maintenance maneuver design because that process propagates spacecraft trajectories for up to 6 months.

Figure 2 plots two quantities: 10.7-cm radio flux from the Sun and Earth's magnetic activity. The figure compares long-term flux predictions (made at launch) with real-time observations, highlighting the departure of solar and geomagnetic activity in Science Phase from their expected behavior. Solar flux hovered around the model's 5th percentile level for most of 2016, while terrestrial magnetic field strength was even lower with respect to its model. For example, on January 10, 2017, observed solar flux was at the 1th per-centile level.

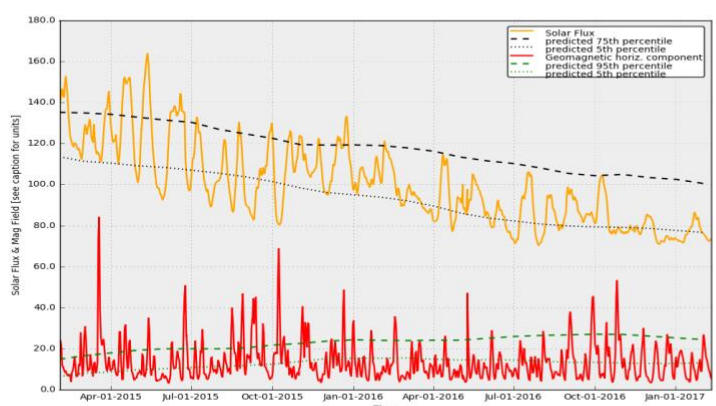

Figure 2. Solar flux and geomagnetic index, A_p: Predicted vs. Observed. Predictions are from MSFC, observations from SWPC. Units for flux are 10^4 Jansky; units for A_p are non-dimensional.

Orbit Trending

The requirement on the down-track component of the observatory's position is to remain within 600 m of its on-board (predicted) ephemeris[6]. This is the reason TARDIS was built – conservative, early studies had suggested that orbit propagations longer than 1-day would be in error by greater than 600 m (3σ), thereby requiring daily ephemeris uploads (see section "TARDIS").

Figure 3 is representative of navigation's short-term predictive capability. Not only does Navigation easily satisfy down-track accuracies for a single day, even 3- and 4-day predictions are often successful. As reinforced in Figure 4, short-term trending has held up throughout Science Phase. The legend in Figure 4 denotes successive daily OD solutions, starting on February 1, 2017. An orbit propagation delivered on February 1, 2017 (OD0731_v00) was, 10-days later, in error by only 550 m. So for this particular solution, prediction was reliable for 10-days. Figure 4 also confirms that, as prediction time decreases so does its error.

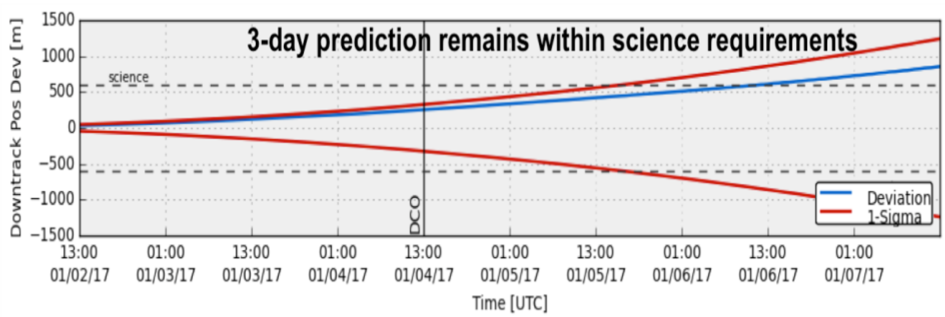

Figure 3. 3-day ephemeris trending.
Jan. 1 prediction compared to Jan. 4 reconstruction.
Blue line is difference between those trajectories. DCO denotes reconstruction 'data cutoff'.

No down-track violations have occurred in Science Phase. The combination of daily product deliveries and a roughly 4-day prediction capability has immunized science requirements against the 0.5% product delivery failure rate. That is, when product delivery failures do occur, pre-existing products continue to satisfy requirements until an updated delivery occurs.

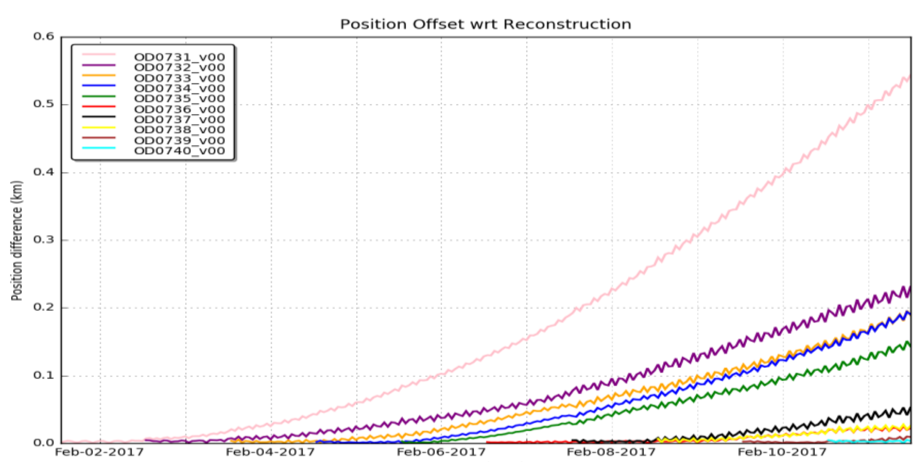

Figure 4. 10-day ephemeris trendings.
Comparison of multiple predictions with respect to reconstruction.

Ground Track

Orbit maintenance depends upon atmospheric conditions months away since drag effects on the observatory are cumulative.

The atmosphere is modeled with Drag Temperature Model (DTM), a thermospheric description of the upper atmosphere incorporating solar radio flux and terrestrial magnetic activity as well as empirical satellite drag data to calibrate its settings. DTM is valid for altitudes from 200 to 1200 km[7].

The observatory's observations are designed such that the observatory's projected track onto the ground remains within +/-20 km laterally of the reference trajectory's ground track[2]. In orbit, in the vertical direction, position requirements are +/-1 km radially from the reference trajectory[8]. These respective boundaries define the Science Orbit "corridor". Periodic drag make-up maneuvers (called orbit trim maneuvers – OTMs) keep the observatory within its corridor.

Plots of the observatory's path within the Science Orbit corridor are shown in Figure 5 (ground track) and Figure 6 (altitude). A significantly more-tenuous-than-modeled atmosphere was experienced in the latter half of 2015 and throughout 2016, leading to minor violations of ground track requirements. (The violations did not degrade science products. See the upcoming "Science Results" section.)

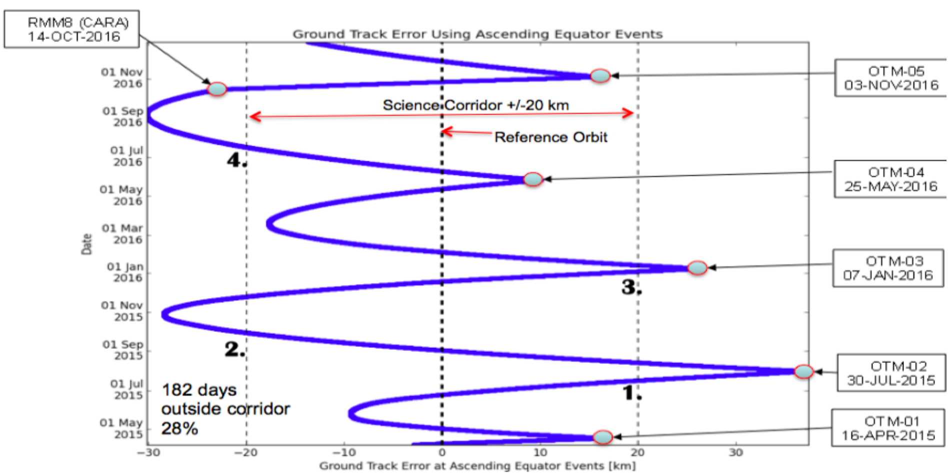

Figure 5. Science Corridor and Observatory Ground Track. See Table 5 for key to integers on plot.

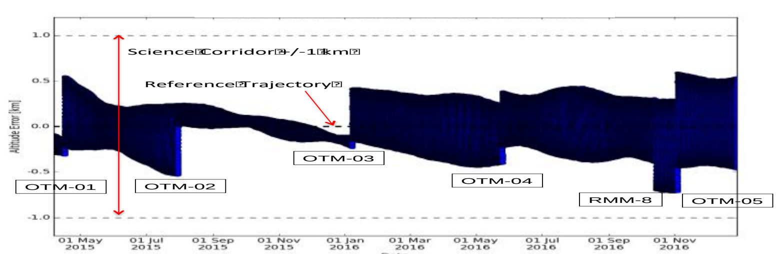

Figure 6. Science Corridor and Observatory Altitude.

2 Defined at the ascending node.

In Figure 5, drag make-up maneuvers are labeled as OTMs; RMM is short for Risk Mitigation Maneuver. Ground track corridor violations are indicated with the numerals 1-4; an explanation key to those violations is provided in Table 5. The magnitudes of OTM-2 and OTM-4 were (in hindsight) too large and this led to ground track crossings of the western boundary. The explanation for the overshoot is given in Table 5.

No altitude violations occurred.

Table 5. Key to Figure 5.

Integer	Explanation
1	Project decision to delay OTM-2 due to synthetic aperture radar failure
2	Imperfect design of OTM-2 - OTM-2 design incorporated 50th percentile solar flux, consistent with flux models and flux measurements at the time. Actual flux level 2 months later had decreased to 5th percentile.
3	Project decision to delay OTM-3 due to spacecraft anomaly
4	Imperfect design of OTM-4 - OTM-4 design incorporated 5th percentile flux, consistent with measured flux at the time (yet *less than* the model). Actual flux level 6 weeks later had decreased to 2th percentile.

Atmosphere Mismodelling

Extreme flux *residuals* (observed versus modeled) should show up as mismodelling in the orbit determination. The negative slope of the blue trend line in Figure 7 illustrates an increasing divergence in atmosphere density between prediction and estimate. DTM's predicted density (based on MSFC predicted flux) and the daily OD density estimates (based on SWPC observed flux) are separated by 30% at the end of 2016. Moreover, the residual mean in Figure 7 is -10% (standard deviation of 25%). While not statistically significant, a 2-year negative bias is another indicator of unusually low flux levels. This atmosphere mismodelling explains the overshoots at 2 and 4 in Figure 5.

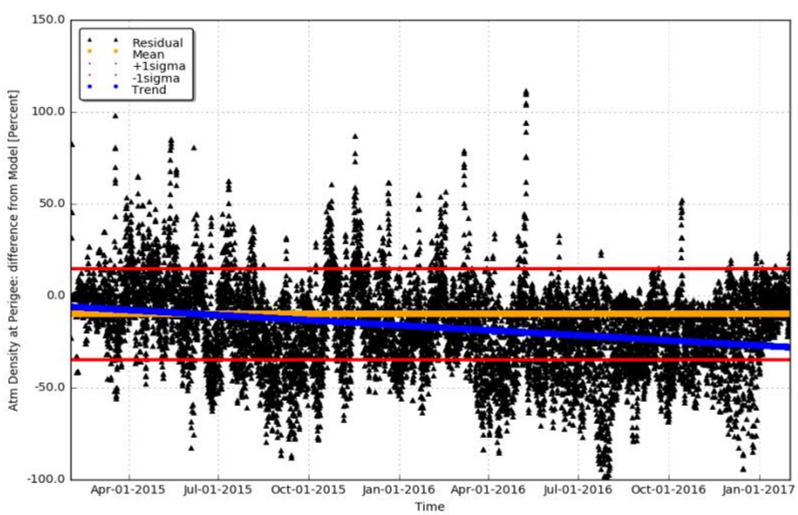

Figure 7. Inconsistency between Modeled Density and Estimated Density (at perigee).

Timing Error

Errors in ephemeris timing (plus an overlay of solar flux history) are shown in Figure 8. Timing error is dominated by maneuver execution errors. The second largest contribution to timing error is spacecraft drag uncertainty. Thus in general, as flux levels decreased, so has timing error. The Project requirement levied on orbit timing error after 10-days (without a trim maneuver in the arc) is 7 seconds (3σ). This requirement is being satisfied with lots of margin, as shown in Figure 8.

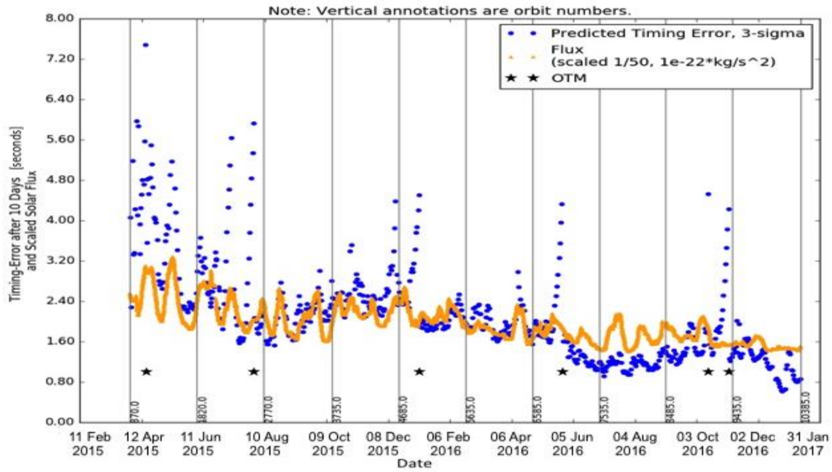

Figure 8. Timing Errors, OTM locations, and Solar Flux.

MANEUVERS IN SCIENCE PHASE

Five drag make-up maneuvers have occurred in Science Phase, or approximately 1 OTM every 5 months (fewer maneuvers than expected because of low flux levels). Maneuver performance has been satisfactory – all burns have executed within ~1σ of expectation. Propellant consumption is only 23% of the Science Phase's budgeted propellant use. 76 kg of propellant (out of 80 kg at launch) remain in the tank.

Table 6 shows all maneuvers performed in Science Phase, including the risk mitigation maneuver.

Table 6. Science Phase Maneuver Performance.

Name	Mission Day	Date, UTC	Reconstructed ΔV, cms^{-1}	Error, σ
OTM-1	76	April 16, 2015 17:20:02	21.25	0.8
OTM-2	181	July 30, 2015 17:07:58	15.43	0.9
OTM-3	342	January 7, 2016 18:23:33	15.55	1.1
OTM-4	481	May 25, 2016 17:55:31	9.15	1.1
RMM-8	623	Oct 14, 2016 15:56:00	8.30	0.8
OTM-5	643	Nov 3, 2016 18:21:40	15.88	0.2
		Total ΔV:	85.6	

CARA MONITORING

The SMAP Project established an interface with NASA's Conjunction Assessment and Risk Analysis group (CARA), located at NASA Goddard Spaceflight Center[9]. CARA's charter is to communicate collision-avoidance information to the Earth-orbiting spacecraft community. To this end SMAP delivers daily ephemeris files to CARA and works with them to identify and assess risks of conjunction with orbital debris, and if needed plan and execute risk mitigation maneuvers to avoid collision.

Conjunction risk is measured with collision probability, P_c. SMAP uses a collision probability of $P_c = 4.4e\text{-}4$ to demark the threshold of high-risk collisions[10]. Figure 9 is a graphical overview of CARA alerts issued to SMAP since launch. Over a 22-month period from April 1, 2016 to February 1, 2017 SMAP received 4 high-risk alerts. One of those alerts was acted upon and an RMM was executed on Oct 14, 2016, as shown in Table 6. The other high-risk alerts ultimately posed no threat and no maneuvers were performed. The ratio of performed RMMs to high-risk alert notifications has been 14% per year.

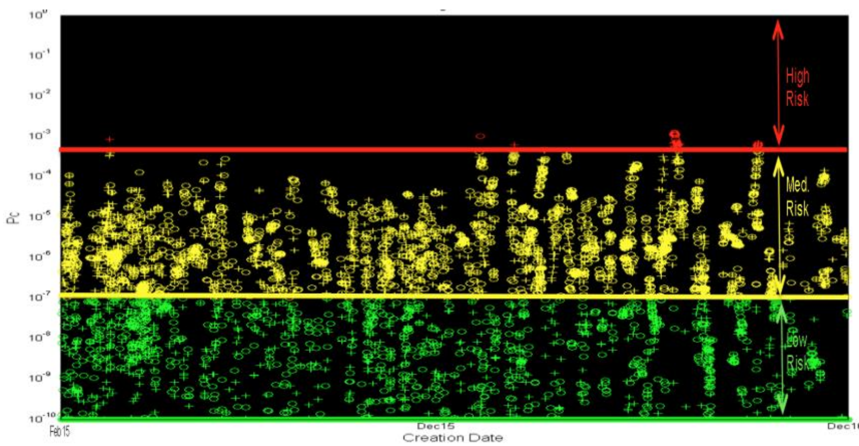

Figure 9. SMAP Conjunction Risk [Megan Johnson, CARA]. Red, yellow, green indicate high, medium and low collision risk.

SCIENCE RESULTS

The quality of SMAP's science output is high. Radiometer results are out-performing mission requirements, exceeding them by 33%[11,12]. Evidently then, no degradation in science product has occurred due to ground track violations. This makes sense because the radiometer has a baseline spatial resolution of 40 km on Earth's surface[11], so radiometer-based results are insensitive to minor excursions outside the corridor.

A representative soil moisture map produced by SMAP in 2015 is shown in Figure 10. SMAP has the capability of producing planet-wide maps such as this every 3-days[13].

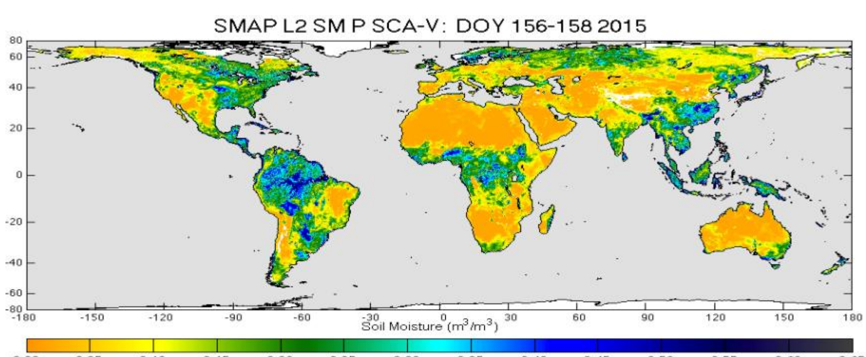

Figure 10. Planetary Soil Moisture Map, June 5-7 2015.

SUMMARY

SMAP's launch on January 31, 2015 coincided with the beginning of the low activity phase of Solar Cycle 24, so reduced solar flux levels were expected. Nevertheless, unusually low flux levels have been experienced and this lack of solar activity led to significantly less atmosphere drag acting on the spacecraft, in turn leading to fewer orbit maintenance maneuvers and thereby increasing propellant margin.

Low flux levels contributed to corridor overshoot. All corridor overshoots have been *minor* and have **not** degraded science products even though, using time as a metric, as of February 1, 2017 the observatory had been beyond the lateral boundaries of the corridor for 28% of Science Phase. All corridor violations are a direct consequence of Project decisions to delay and/or cancel maneuver implementations because allocating resources for orbit maintenance without a demonstrable need yields no marginal benefit.

Other than corridor overshoot, the navigation subsystem is in compliance with all Science Phase requirements.

Automated navigation on SMAP is a proven success. Over a 19-month period 95% of product deliveries were made on time. TARDIS, the dominant automaton in this process, is reliable and successfully performed its duties 99.3% of the time. Automation of routine SMAP navigation tasks has enabled a reduction in navigation personnel to 25% of the workforce levels that would otherwise have been required.

ACKNOWLEDGMENTS

George Carlisle led the Mission Design Team before launch. Sara Hatch spent many hours building the reference trajectory and we thank her for those efforts. Ian Roundhill's cognizance of TARDIS and his expert advice were much valued during TARDIS' start-up activities. Daniel Lubey contributed to both pre-launch preparations and to post-launch OD support.

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REFERENCES

1 K. Kellogg et al, "NASA's Soil Moisture Active Passive (SMAP) Observatory", *IEEE Explore*, 978-1-4673-1813-6/13, 2013, http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6496938

2 Cheryl Gramling, NASA Goddard Space Flight Center, private communication, 2014.

3 I. Roundhill, and R.M. Kelly, "TARDIS: An Automation Framework for JPL Mission Design and Navigation", *SpaceOps 2014 Conference Proceedings*, AIAA 2014-1726. doi: 10.2514/6.2014-1726

4 NOAA Space Weather Prediction Center, Boulder Colorado, http://www.swpc.noaa.gov/products-and-data

5 NASA Marshall Space Flight Center, Space Physics Division, Huntsville Alabama https://sail.msfc.nasa.gov/solar_report_archives/

6 SMAP Navigation Plan, D-46006, Section 2.5, Jet Propulsion Laboratory, Pasadena California, August 1, 2014.

[7] F. Barlier et al, “A thermospheric model based on satellite drag data”, *Annals of Geophysics*, vol.34, no. 1, 1978, pp. 9-24.

[8] SMAP Navigation Plan, D-46006, Section 2.2, Jet Propulsion Laboratory, Pasadena California, August 1, 2014.

[9] NASA Goddard Space Flight Center, Greenbelt Maryland, CARA Division, https://satellitesafety.gsfc.nasa.gov/cara.html

[10] CARA Users’ Forum, Lauri K. Newman, NASA Goddard Space Flight Center, Greenbelt Maryland, 2014.

[11] J. Piepmeier et al, “SMAP L-Band Microwave Radiometer: Instrument Design and First Year on Orbit," *IEEE Transactions Geoscience Remote Sensing* [Online.] doi: 10.1109/TGRS.2016.2631978, 2016.

[12] R.H. Reichle et al, “SMAP Mission L4_SM Data Product Assessment (Version 2 Validated Release)”, NASA GMAO Office Note, No. 12 (Version 1.0), p 55, 2016.

[13] S.R. Chan et al, “Assessment of the SMAP passive soil moisture product”, *IEEE Transactions on Geoscience and Remote Sensing*, 54(8), pp. 4994–5007, 2016.